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by

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Forward Osmosis in Reverse Osmosis Concentrate Management

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Certificate of Authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Shahzad Jamil

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Date: 08-11-2017

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Abstract

The production of fresh water and the disposal of wastewater are the major challenges of the last few decades. Reverse osmosis (RO) membrane plants are used extensively for brackish water desalination and industrial water purification. These plants operate at about 75% product water recovery so that about 25% of feed water is wasted as concentrated brine. The large quantities of concentrated brine generated has a disposal problem especially when the plants are located inland. Because of high disposal costs there is need to re-use and conserve water. RO reject concentrate (brine) is being increasingly processed to recover additional potable water. In order to achieve higher recoveries, therefore, alternate processes are used. Out of them forward osmosis is attractive.

FO water desalination technique uses the natural osmotic pressure of the draw solute to drive osmosis rather than hydraulic pressure. Fertilizer drawn forward osmosis (FDFO) has been applied as a low cost water desalination option for agriculture purposes. This technique is further investigated by applying pressure on feed solution to enhance water permeate flux, which is called pressure assisted fertilizer drawn forward osmosis (PAFDO). PAFDO can enhance final dilution of the fertiliser draw solution beyond osmotic equilibrium concentration. In simple terms, this technique can be considered combination of FO and low pressure reverse osmosis RO. Due to the low cost desalination potential, the FO and PAFO processes have gained attention of the research community.

Reverse osmosis concentrate (ROC) produced in water reclamation and desalination plants can endanger the environment if it is not treated before discharge. Volume minimisation of ROC can help in its easy disposal. The study examined the use of

forward osmosis (FO and PAFO) with and without granular activated carbon (GAC) fixed bed adsorption pretreatment for volume minimisation of ROC and removal of organic micropollutants.

In this study FO and PAFO were assessed in treating reverse osmosis concentrate using a low concentration of (KCl) as fertiliser DS. A low concentration of KCl (0.25 M) was chosen as DS and it was diluted to 0.14 M KCl during the FO operation due to transport of water permeate flux from feed solution. This diluted KCl solution can be used for direct fertigation, as the past studies showed successful use of 10 Kg/m^3 (≈0.13 M KCl) for fertigation.

Forward osmosis (FO) and nanofiltration (NF) membranes were tested to treat the ROC for possible water reuse. Due to very small pore sizes of FO membranes were used in nano-filtration mode to treat ROC from water reclamation plant. Commonly used NF membrane was good option for removing for organic compounds including micropollutants from wastewater however, most of inorganic compounds passed through the NF membrane. Since the FO membranes have pore size less than most of NF membranes, they also removed inorganic ions present in ROC. In this way the resultant permeate flux was able to be recycled back to RO unit to increase overall efficiency of the plant.

Fouling and scaling is an important and inevitable phenomenon in FO membranes as well. Lower membrane fouling and/scaling implies more product water, less cleaning and longer membrane life, thereby reducing operational and capital costs. It was observed that scaling and fouling were not fully reversed in FO/PAFO by physical cleaning. However, the physical cleaning followed by chemical cleaning could almost fully restore the activity of the membrane.

In this study, the membrane bioreactor (MBR) and granulated activated carbon were used as pretreatment methods to curtail organic fouling of the membrane. Both these pretreatment processes were proved to be successful to reduce total organic carbon of ROC including a majority of micropollutants. Moreover, inorganic carbon of ROC was reduced by acid pretreatment. These pretreatment processes resulted in high permeate water flux and less membrane fouling.

Keywords: Pressure assisted forward osmosis, Nano-filtration, chemical cleaning, membrane, Membrane bioreactor.

Journal Articles Published

1) **Jamil, S.,** Jeong, S. & Vigneswaran, S. 2016, 'Application of pressure assisted forward osmosis for water purification and reuse of reverse osmosis concentrate from a water reclamation plant', Separation and Purification Technology, vol. 171, pp. 182-90.
2) **Jamil, S**., Loganathan, P., Kazner, C. & Vigneswaran, S. 2015, 'Forward osmosis treatment for volume minimisation of reverse osmosis concentrate from a water reclamation plant and removal of organic micropollutants', Desalination, vol. 372, pp. 32-8.
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2. **Shahzad Jamil**, P. Loganathan, S. Vigneswaran; Forward Osmosis and GAC adsorption hybrid system for RO concentrate volume minimisation and organic micropollutants removal, *Proceedings of the 9th IWA Micropol and Ecohazard Conference 22 - 25 November 2015, Singapore.*

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4. **Shahzad Jamil**, Christian Kazner, Sherub Phuntsho, Hokyong Shon, Thomas Wintgens2 and Saravanamuth Vigneswaran, Forward Osmosis for the Treatment of RO Concentrate from Water Reclamation: Process Performance and Fouling Control, 7th IWA Specialized Membrane Technology Conference · Toronto, Canada · 25 – 29 August 2013.

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Nomenclature

ICP	:	Internal concentration polarization
FDS	:	fertilizer draw solution
TOC	:	Total organic carbon
GAC	:	Granulated activated carbon
MDL	:	Method detection limit
OMs	:	Organic micropollutants
ROC	:	Reverse osmosis concentrate
TIC	:	Total inorganic carbon
Jw	:	water flux (L/m^2 h)
P	:	hydraulic pressure (bar)
t	:	membrane thickness (µm)
PAFO	:	Pressure assisted forward osmosis
PAFDO	:	pressure assisted fertilizer drawn forward osmosis
TDS	:	Total dissolved solids
MF	:	Microfiltration
UF	:	Ultrafiltration
NF	:	Nanofiltration
RO	:	Reverse osmosis
FO	:	Forward osmosis
FS	:	Feed solution
DS	:	Draw solution
AL	:	Active layer
SL	:	Support layer
MBR	:	Membrane biological reactor
CP	:	Concentration polarization
ECP	:	External concentration polarization
ICP	:	Internal concentration polarization
RSF	:	Reverse solute flux
AL-DS	:	Active layer – draw solution
AL-FS	:	Active layer - feed solution
DI	:	Deionized
MD	:	Membrane distillation
PSf	:	Polysulfone
PES	:	Polyethersulfone
PA	:	Polyamide
CTA-ES	:	Cellulose triacetate with embedded polyester screen
TFC-ES	:	Thin flim composite with embedded polyester screen
PSF	:	Polysulphone
MWCO	:	Moleculor weight cut-off
Norm.	:	Normalized
VMD	:	Vacuum Membrane Distillation
ZLD	:	Zero liquid discharge

BSA	:	Bovine serum albumin
HA	:	Humic acid
TOC	:	Total organic carbon
SEM	:	Scanning electron microscope
LMH	:	$L/m^2/h$
HTI	:	Hydration Technology Innovations
DBPs	:	Disinfection By-Products
BTSE	:	Biological treated wastewater
WWTPs	:	Wastewater treatment plants

List of Symbols

A	:	Water permeability coefficient ($L.m^{-2}.h^{-1}.bar^{-1}$)
B	:	Salt permeability coefficient ($m.s^{-1}$)
C	:	Solute number density (L^{-1})
c	:	Solute concentration
D/Ds	:	Diffusion coefficient ($m^2 s^{-1}$)
Dh	:	Hydraulic diameter (m)
D	:	Salt diffusion coefficient
I	:	Intrinsic membrane structural properties
J_s	:	Solute flux ($g.m^{-2}.h^{-1}$)
J_w	:	Water flux ($L\ m^{-2}\ h^{-1}$)
J_w, sp	:	Specific water flux ($L\ m^{-2}\ h^{-1}\ bar^{-1}$)
k	:	Mass transfer coefficient
M	:	Solute molar concentration ($mol.\ L^{-1}$)
M	:	Molar concentration of the solution
Mw	:	Molecular weight ($g.mol^{-1}$)
N	:	Moles of solute (mol)
n	:	Van't Hoff factor
P	:	Applied hydraulic pressure (bar)
Re	:	Reynolds number
Sc	:	Schmidt number
T	:	Absolute temperature (in K)
t	:	Thickness of the membrane (m)
Δt	:	Time interval (h)
ΔV	:	Volume change (L)
ΔP	:	Pressure change (bar)
Sh	:	Sherwood number
μ	:	Conductivity (mS/cm)
S	:	Structural parameter
σ	:	rejection coefficient
π	:	Osmotic pressure

Superscripts/subscripts

w	:	Water
s	:	Solute
m	:	Membrane
i	:	Interface
D, b	:	Draw, bulk
F, b	:	Feed, bulk
F, m	:	Feed, membrane
D, m	:	Draw, membrane
W, sp	:	Water, specific

Greek letters

π	:	Osmotic pressure (Pa)
φ	:	Osmotic pressure coefficient
σ	:	Reflection coefficient,
ε	:	membrane porosity
β	:	van't Hoff coefficient
τ	:	pore tortuosity

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